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SIMULATION OF SOIL TEMPERATURE VARIATION FOR GEOTHERMAL APPLICATIONS

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ABSTRACT

This paper aims to predict ground temperature variation with depth for time variant ambient air temperature and solar radiation data for Jamshedpur, India. Fourier series and CFD techniques have been employed to determine diurnal and annual temperature variation for the hottest and the coldest day of the year 2015.The diurnal temperature variation is up to 0.2m depth of soil whereas annual temperature variation is up to 3m depth.

Key words: Soil temperature; CFD Simulation; Fourier series.

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NOMENCLATURE

α	Thermal Diffusivity of soil (m^2/s)	k	Thermal conductivity of soil (W/mK)
α_0	Absorptivity of solar radiation at the surface	T	Soil temperature (K)
c	Specific heat(J/kgK)	T_a	Air temperature (K)
ε	Emissivity of soil surface	T_e	Effective temperature (K)
h	Convective heat transfer coefficient on the soil surface (W/m^2K)	t	Time (s)
ΔR	Long-wave radiation (W/m^2)	ω	2Π/period (rad/s)
ρ	Density of ground (kg/m^3)	y	Vertical axis (m)
S	Intensity of solar radiation (W/m^2)		
m	Number of terms of Fourier series		

1. INTRODUCTION

Prediction of soil temperature has important applications such as the passive heating and cooling of buildings and agricultural greenhouses. For design of earth-to-air heat exchangers it is necessary to know the ground temperature at different depths. The air temperature and solar radiation are the main meteorological parameters to change the regular periodic variation in thermal regime of the soil. Soni et al. [1] presented excellent review of research in the area of earth air heat exchangers.

Khatry et al. [2] presented a technical note for ground temperature variation with depth taking into account the periodicity of solar radiation and atmospheric temperature for Kuwait. Bharadwaj and Bansal [3] calculated daily and annual variations of the ground temperature for dry sunlit, wet sunlit, dry shaded and wet shaded surface conditions at New Delhi. Mihalakakouet.al.[4]and Mihalakakou [5] estimated ground surface temperature for bare and short-grass covered soil employing Fourier analysis and validated results by measurements in Athens and Dublin. Ozgeneretal.[6] measured and predicted temperature of soil at various depths in Izmir, Turkey.

In the present investigation temperature variation of soil for dry sunlit condition has been modeled employing Fourier as well as CFD techniques for time varying boundary condition for Jamshedpur, India.

2. MATHEMATICAL FORMULATION

The variation of ground temperature followed one-dimensional, transient heat conduction equation given by [9].

$$\frac{\partial^2 T(y,t)}{\partial y^2} = \frac{1}{\alpha}\frac{\partial T(y,t)}{\partial t} \tag{1}$$

Solution of above equation is subjected to the boundary condition at the ground surface given by [3]:

$$-k\left.\frac{\partial T}{\partial y}\right|_{y=0} = h(T_a - T_{y=0}) - \varepsilon\Delta R + \alpha_0 S \tag{2}$$

Left side of above equation shows the conduction through ground surface. First term of right side equation shows convective heat transfer between ground surface and air. Second term of above equation is long wave radiation and third term denotes solar radiation absorbed by the ground surface. The above equation can be written in the form of general convective heat transfer boundary condition as:

$$-k\left.\frac{\partial T}{\partial y}\right|_{y=0} = h(T_e - T_{y=0}) \tag{3}$$

The effective temperature T_e can be expressed as,

$$T_e = T_a + \alpha_0 S / h - \varepsilon\Delta R / h \tag{4}$$

2.1. Fourier Analysis

Ambient air temperature T_a and solar radiation intensity Svary periodically which can be expressed as Fourier series. The effective temperature T_e will also be expressed as Fourier series:

$$T_e = a_0 + \sum_{m=1}^{\infty} a_m \cos(m\omega t - \psi_m) \tag{5}$$

The solution of one dimensional heat conduction equation (1) for T to be finite when

$y \to \infty$ become [9]:

$$T(y,t) = A_0 + \sum_{m=1}^{\infty} A_m \exp[i(m\omega t) + \alpha_m y) \tag{6}$$

Where

$$\alpha_m = -(1-i)(\omega\rho c m / 2k)^{1/2} \tag{7}$$

Substituting for T_e and $T(y,t)$ from equation (5) and (6) respectively, into the equation (3), one obtains [3]:

$$T = a_0 + \sum_{m=1}^{\infty} B_m \exp(-m^{1/2}\alpha y)\cos(m\omega t - m^{1/2}\alpha y - \psi_m - \beta_m) \tag{8}$$

Where

$$B_m = a_m[(1+m^{1/2}\mu)^2 + m\mu^2]^{-1/2} \tag{9}$$

$$\mu = (\frac{k\omega\rho c}{2})^{\frac{1}{2}} / h \tag{10}$$

$$\beta_m = \tan^{-1}\left[\frac{m^{1/2}\mu}{(1+m^{1/2}\mu)}\right] \tag{11}$$

2.2. CFD Analysis

The ground is considered as semi-infinite solid subject to time variant boundary condition. Two dimensional axis-symmetry geometry of soil 10m depth and 1m radius is created in ANSYS workbench. Structured uniform mesh size of 0.05m and time step of 5min have been considered optimum for simulation. The geometry and mesh of the model are shown in Fig.1. The temperature field in the soil has been obtained by solving energy equation through FLUENT 14.5 with convergence criteria set to 10^{-6}. CFD simulation has been run for one year with time variant hourly data for ambient air temperature and solar radiation employing user defined function.

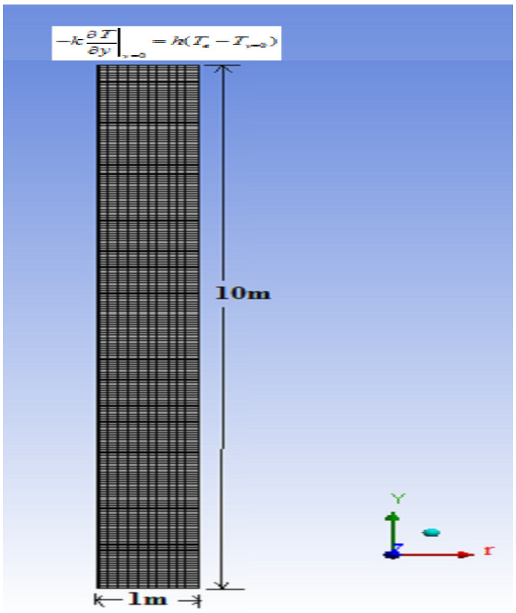

Figure 1 Geometry and Mesh for CFD analysis

3. RESULTS AND DISCUSSION

For Fourier and CFD analysis of ground temperature variation, the soil is taken as a homogeneous and its physical properties are assumed constant as given in [1]:

k = 0.51 W/mK, ρ= 2050 Kg/m^3, c_p = 1842.3 J/Kg K

α_0=0.9, ε=1, ΔR=63.1 W/m^2 and h=22.7 W/m^2K (at 3 m/s wind speed).

The temperature distribution in the soil depends on the air temperature and solar radiation. Data for ambient air temperature and solar radiation are continuously measured every minute at National

Institute of Technology, Jamshedpur, India [11]. Diurnal variation of hourly ambient air temperature and solar radiation for the hottest day and the coldest day are shown in Fig.2 and Fig.3 respectively. The hottest day for the year 2015 is 10 June whereas coldest day for the same year is 28 December. Annual variation of daily average ambient air temperature and solar radiation are shown in Fig.4 and Fig.5 respectively. These variations can be expressed as Fourier series with six harmonics which are sufficient for matching all the given data with R^2= 99% approximately. Fourier series coefficients for ambient air temperature, solar radiation and effective temperature are given in Table 1, Table 2 and Table 3 respectively.

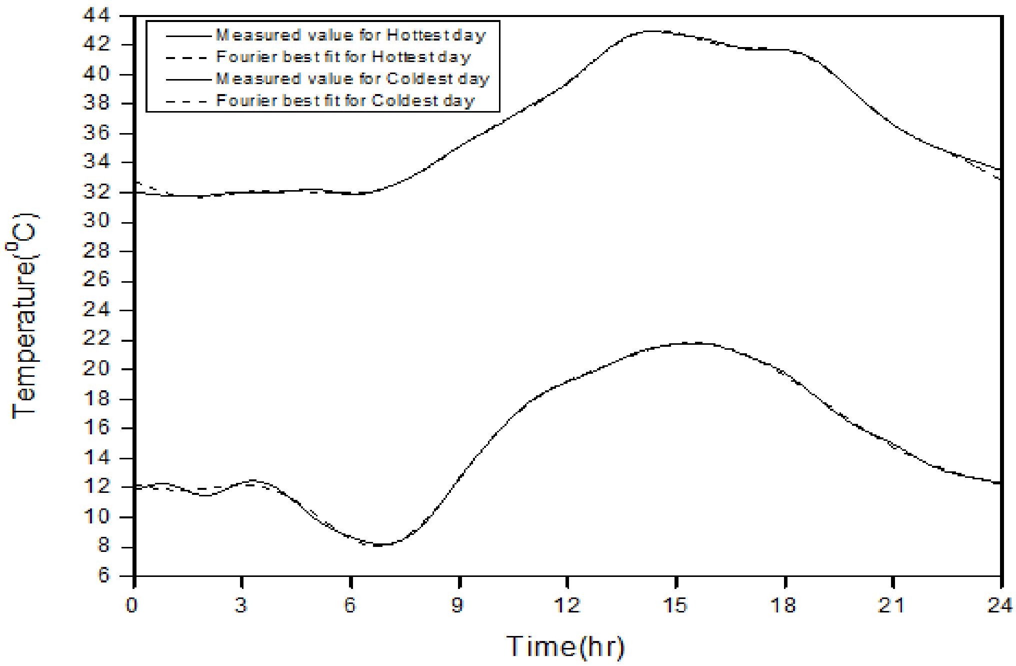

Figure 2 Hourly ambient air temperature for the hottest day (10th June) and the coldest day (28th Dec) 2015 in Jamshedpur, India

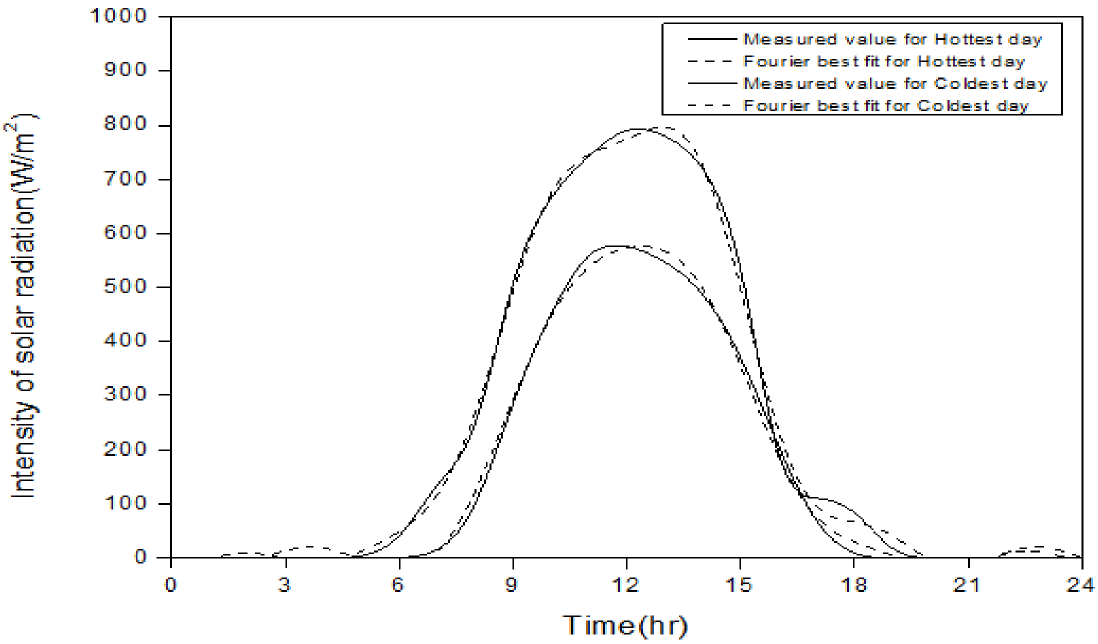

Figure 3 Hourly solar radiation intensity for the hottest day (10th June) and the coldest day (28th Dec), 2015 in Jamshedpur, India

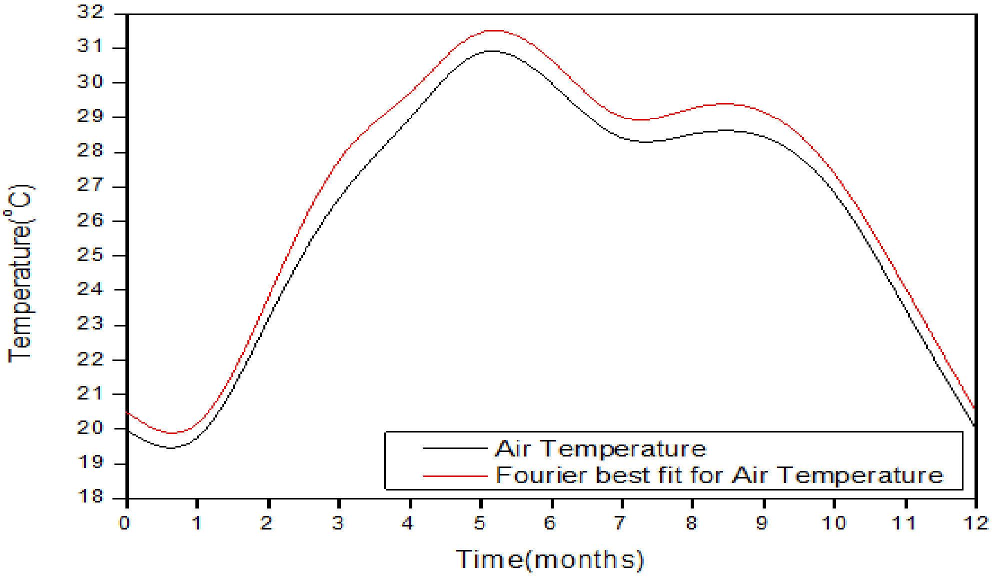

Figure 4 Monthly average ambient air temperature in Jamshedpur, India for year 2015

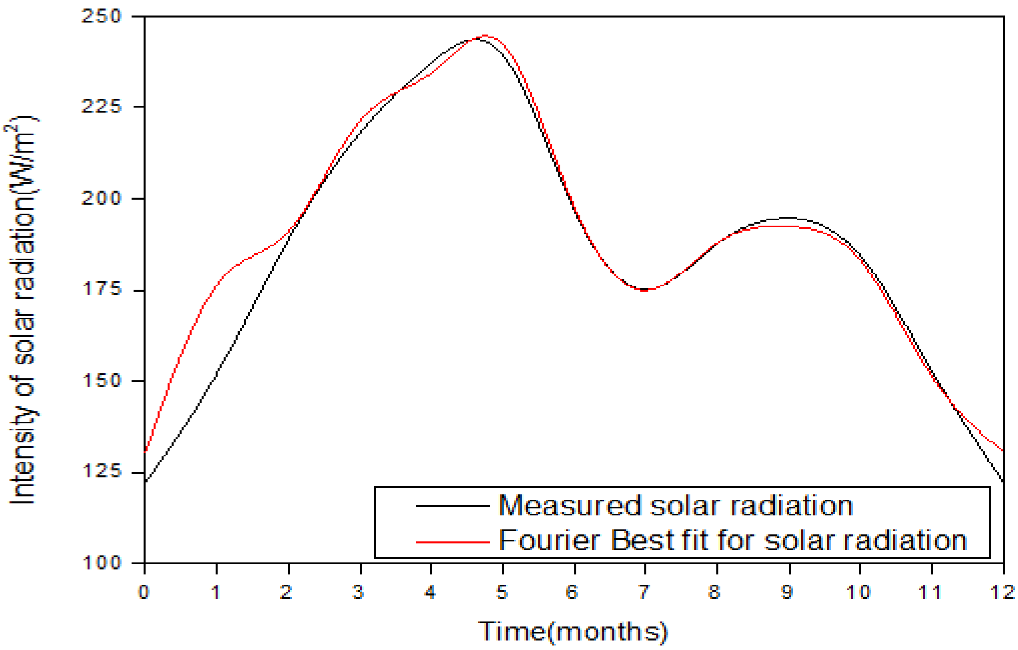

Figure 5 Monthly average solar radiation intensity in Jamshedpur, India for the year 2015

Table 1 Coefficients of Fourier series for ambient air temperature (T_a) in Jamshedpur, India

		0	1	2	3	4	5	6
Annual	Am	26.99	4.910976	2.573121	0.916304	0.942657	0.479378	0.517238
	ψ_m		-0.08008	0.339793	-0.35989	1.013456	-0.37594	0.104728
Hottest day	Am	36.58	5.74124	0.772853	0.73958	0.121835	0.512296	0.138914
	ψ_m		0.949696	-1.27728	-0.02204	-0.7817	-0.7484	0.6251
Coldest day	Am	15.11	5.801712	1.907854	1.857241	0.685227	0.234354	0.038269
	ψ_m		1.005455	1.113712	0.398105	1.202187	0.2662	0.039154

Table 2 Coefficients of Fourier series for solar radiation intensity (S) in Jamshedpur, India

		0	1	2	3	4	5	6
Annual	Am	191.7	34.99706	25.98472	14.50651	5.384759	16.90552	9.964501
	ψ_m		-0.93507	0.094001	-1.40186	0.14912	0.428086	-1.35907
Hottest day	Am	232.6	376.6289	195.0089	6.141652	21.08999	38.40026	33.88953
	ψ_m		0.012397	0.009574	-1.26192	-0.86124	-0.39115	0.093973
Coldest day	Am	153.2	261.5779	155.2413	19.99031	15.2605	24.03611	9.634712
	ψ_m		0.07201	0.126848	-0.18749	0.868574	0.596888	0.578877

Table 3 Coefficients of Fourier series for effective temperature *(Te)* in Jamshedpur, India

	m	0	1	2	3	4	5	6
Annual	Am	31.8107	5.915448	3.581173	1.304678	0.905214	1.06062	0.68356
	ψ_m		-0.25852	0.269736	-0.75036	0.66965	0.096553	-0.50745
Hottest day	Am	43.02229	18.88938	7.551657	0.813822	0.957667	2.010426	1.518494
	ψ_m		0.256314	0.107977	-0.29612	-0.85115	-0.48037	0.160371
Coldest day	Am	18.40427	14.58854	7.380677	2.555577	1.27243	1.119579	0.349717
	ψ_m		0.397331	0.344217	0.225846	1.045844	0.437155	0.635142

Figure. 6 and 7 show variation of soil temperature for the hottest and coldest day respectively. Results obtained by Fourier series and CFD methods are close. As the depth of soil increases, amplitude of temperature decreases. After a depth of 0.2m, there is no diurnal variation of soil temperature.

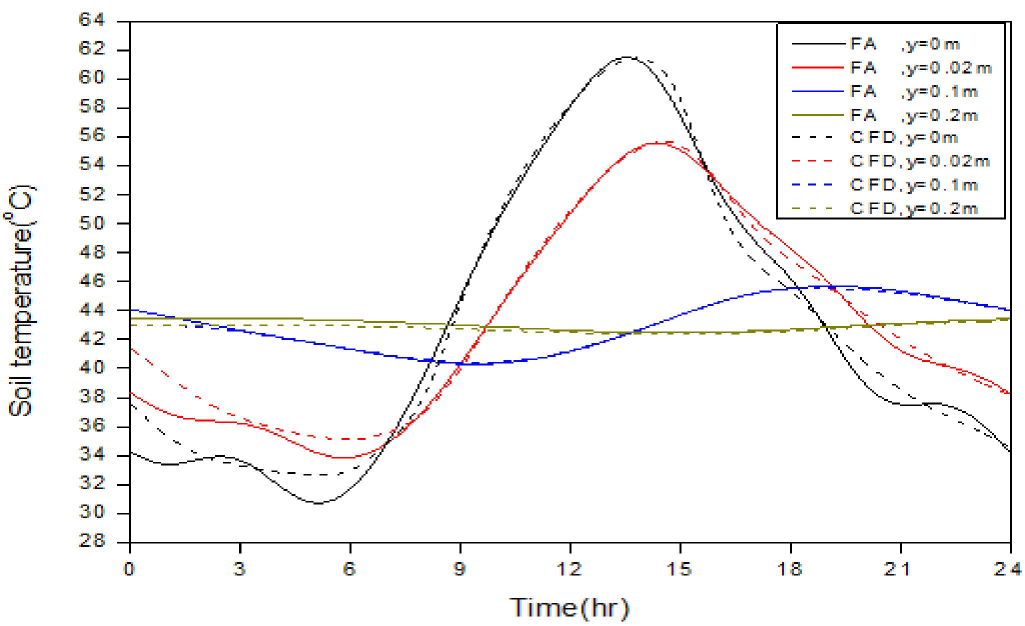

Figure 6 Variation of soil temperature for the hottest day at various depths

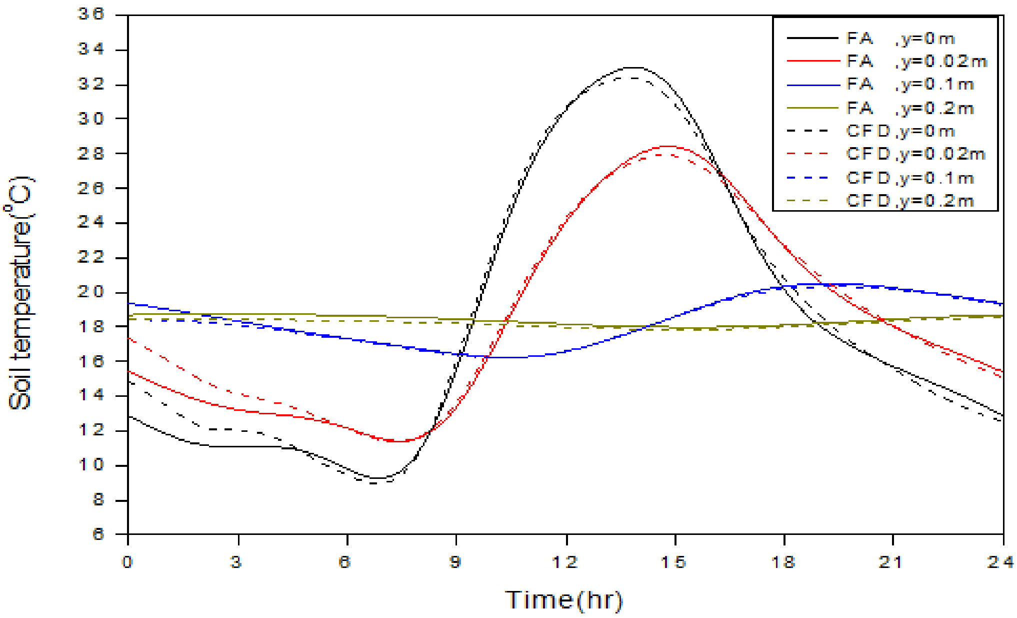

Figure 7 Variation of soil temperature for the coldest day at various depths

Fig. 8 shows annual variation of soil temperature with depth. After a depth of 3m, the soil temperature becomes constant. Results obtained by both Fourier series and CFD methods are close. The minor variation is due to input methods. In Fourier series, data for six harmonics are input whereas CFD simulation is run for monthly data points.

Fig. 9 shows variation of soil temperature depth wise for the hottest day and the coldest day. Diurnal variation of soil temperature is up to 0.2m whereas annual variation is up to a depth of 3m.

Fig.10 shows variation of heat flux on the ground surface for the hottest day and coldest day of the year 2015 in Jamshedpur, India. The heat flux is positive during sunny hour and negative for other time. Net heat transfer during whole day is negligibly small.

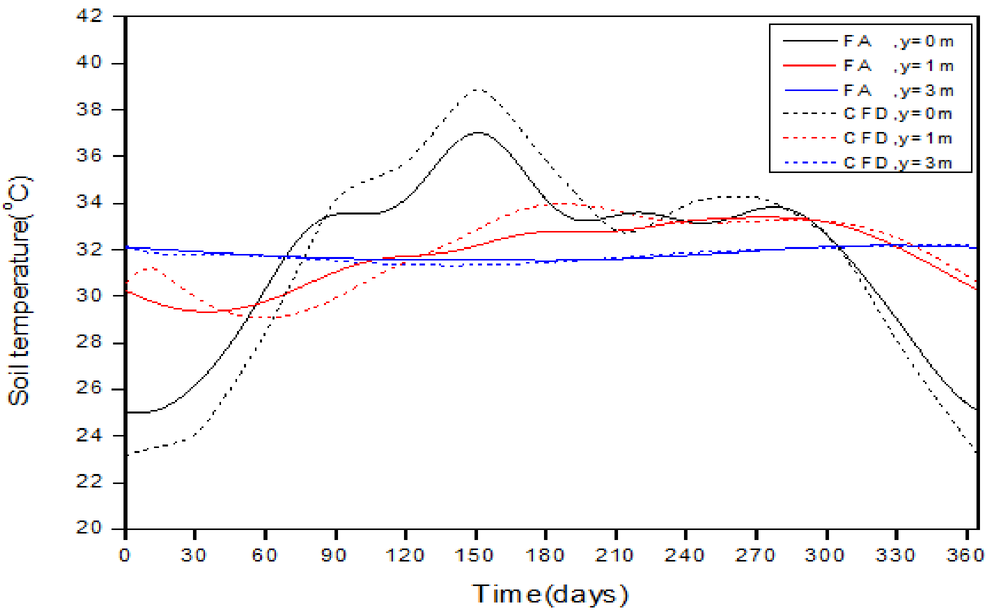

Figure 8 Annual variation of soil temperature with depth

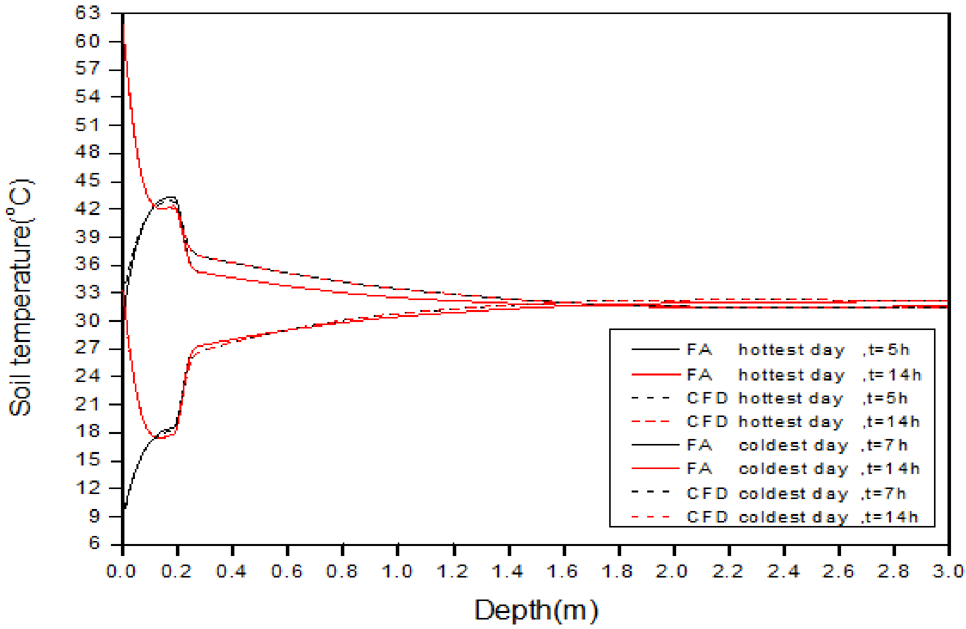

Figure 9 Variation soil temperatures with depth for the hottest and the coldest day

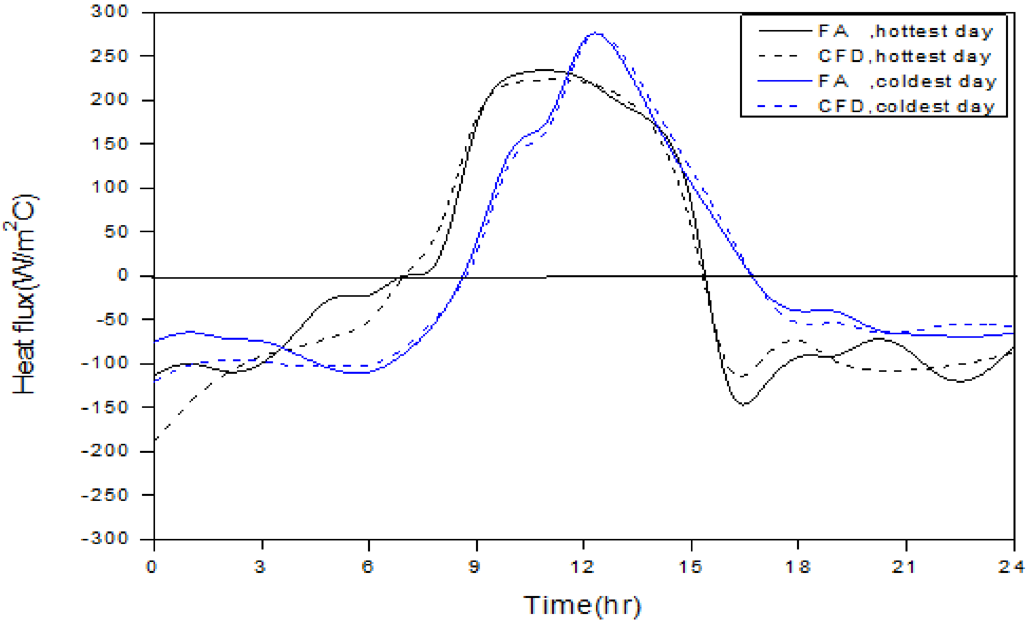

Figure 10 Variation of heat flux over ground surface for the hottest and the coldest day

4. CONCLUSIONS

The present investigation reports results of soil temperature variation with depth in Jamshedpur, India employing Fourier series and CFD methods. Both Fourier series and CFD simulation have been used for the hottest day (10th June), the coldest day (28th December) and whole year 2015. Results obtained by both methods are close. Diurnal variation of soil temperature is found up to depth of 0.2m whereas annual variation is up to 3m of depth.

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